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doi:10.15199/48.2016.07.20

Sensitivity method for evaluating impact of accuracy of the measurement path during ESD generator verification

***Abstract** . The paper contains results of uncertainty estimation during verification of ESD generator parameters by means of sensitivity method in scattering parameters measurement. In addition, basic assumptions and limitations necessary for correct measurement those parameters were described. A calculation example as well as simulation results and graphs have been presented.*

***Streszczenie**. W referacie przedstawiono wyniki analizy metody wrażliwościowej przy pomiarach parametrów S elementów toru pomiarowego podczas weryfikacji generatorów ESD Przedstawiono metodykę pomiarów, zaprezentowano przykładowe obliczenia oraz wykresy uzyskane podczas symulacji. Przedstawiono także założenia metody szacowania niepewności pomiarów wykonywanych przy weryfikacji symulatorów wyładowań elektrostatycznych. (**Wrażliwościowa metoda szacowania niepewności pomiarów wykonywanych przy weryfikacji symulatorów wyładowań elektrostatycznych**).*

Keywords: Sensitivity method, Measurement uncertainty, Electromagnetic compatibility, Electrostatic discharge, ESD simulator.
Słowa kluczowe: metoda wrażliwościowa, niepewność pomiaru, kompatybilność elektromagnetyczna, wyładowania elektrostatyczne

Introduction

Verifying immunity to electrostatic discharge (ESD) is one of the basic tests applied to electric devices to ensure their electromagnetic compatibility. The general rules for conducting such tests are described in standard PE-EN 61000-4-2 [1]. To ensure accuracy of the tests, the simulator undergoes periodic verification in accordance with the regulations contained in this standard. The simplified diagram and measuring track at the ESD generator is depicted in figure 1,2.

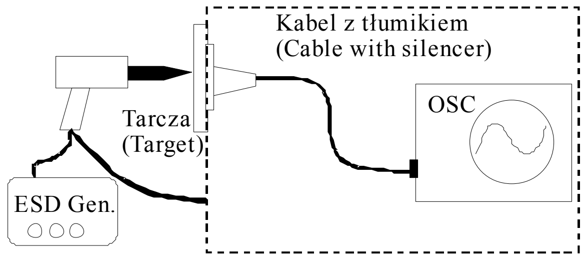

Fig. 1. The simplified diagram to calibration the ESD generator

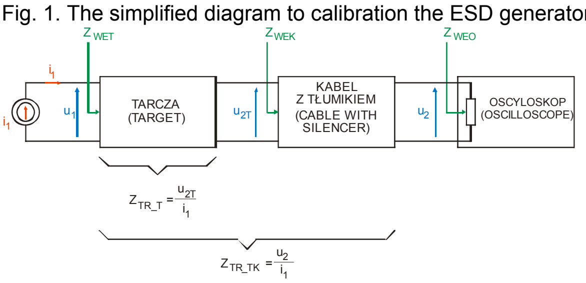

Fig. 2. The measurement track to verify the ESD generator

The measurement setup includes: a target plate, oscilloscope, and cable with attenuator connecting the plate to the oscilloscope. All the elements except the external surface of the target plate are enclosed in a shielded chamber (Faraday cage).

To ensure the reliability of testing the measurement results must be accompanied by an assessment of their uncertainty. Preparing a through calculation of uncertainty is in this case very difficult and time consuming and requires extensive equation and analysis. The accuracy is influenced by the following factors:

- The electrostatic discharge phenomenon involves high -voltage (arc in regular atmosphere occurs at several kV),
- The spectrum characteristics of the ESD discharge current encompasses a range of several GHz,
- Measuring the current pulse requires a specialized oscilloscope with the analog range of over 1 GHz and sampling rate of 10^9 per second,
- Applying complex time-frequency transformations is required to determine the influence of uncertainty of the measurements, such as impact of certain oscilloscope parameters on the accuracy of the current measurements,
- High frequency parameters of the target plate cannot be directly measured, use of special adapters is required.

The main problem encountered during assessment of the uncertainty of these measurements is the relationship of the uncertainty of the measurement path (given as a function of frequency) on the measurements of the ESD current (given as a function of time). These issues are described in [2-5].

Proposed method for estimating callibration uncertainty of the ESD simulator

To ensure the comparability and reproducibility of test results discharge immunity is necessary to verify the ESD waveform output current in the ESD generator. During the verification of the ESD generators must be checked whether the current waveform obtained at the output of the generator conforms to the shape of current recommended by that standard.

The method of estimating the calibration uncertainty of the ESD simulator was described in detail in the doctoral thesis by Tomasz Dróżdż [6].

An analytical pattern of the theoretical waveform current in the ESD generator $i(t)$ is shown below:

(1)
$$i(t)=\frac{i_o}{k_0}\cdot\frac{\left(\frac{t}{\tau_o}\right)^3}{1+\left(\frac{t}{\tau_o}\right)^3}\cdot e^{\frac{-t}{\tau_1}}+\frac{i_1}{k_1}\cdot\frac{\left(\frac{t}{\tau_2}\right)^3}{1+\left(\frac{t}{\tau_2}\right)^3}\cdot e^{\frac{-t}{\tau_3}}$$

Where i_o, i_1 are constants related to current amplitude values, τ_0 , τ_1 , τ_2 , τ_3 - are constants related to the time values of the current, and k_0 , k_1 are constants related to τ coefficients.

The oscilloscope input voltage can be described as a function of frequency using the following formula. In the other calculation the current i_1 will be presented as I_1:

(2)
$$U_2(f)=Z(f)\cdot I_1(f)$$

where $Z(f)$ is the transfer impedance of the entire measurement path, $I_1(f)$ is the Fourrier transformation of the input current value.

The transfer impedance of the entire measurement channel $Z(f)$ can be expressed as a function of admittance parameter Y of the four-terminal network (created by chaining of the four-terminal networks representing the target and the attenuator cable) and the input impedance of the target Z_{WET}. The upper indices in the formulas mean: ^{T}-parameters associated with the shield, ^{K}-parameters associated with connecting cable ^{O}-parameters associated with the oscilloscope.

$$(3)\qquad Z(f)=\frac{U_2(f)}{I_1(f)}=\frac{1-Y_{11}^{TK}Z_{WET}}{Y_{12}^{TK}}$$

The required input impedance of the target Z_{WET} can be expressed as a function of its admittance parameters Y^T and load impedance of the target Z_{OT}, which is comprised of the remainder of the measurement channel, i.e. the cable, attenuator, and the oscilloscope.

The normalizing constants are assumed equal to reference impedances, in this case the impedances of the network analyzer ports, i.e. $r_1=Z_{p1}=50\Omega$, $r_2=Z_{p2}=50\ \Omega$

$$(4)\qquad Z_{WET}=\frac{U_1}{I_1}=\frac{1-Y_{22}^{T}Z_{OT}}{Y_{11}^{T}-Z_{OT}\left|Y\right|^{T}}$$

where: $Y^T=Y_{11}{}^TY_{22}{}^T-Y_{12}{}^TY_2{}^T$.

Detailed description of the mathematical model and the computer program utilized in the method is described in the doctoral thesis by Tomasz Dróżdż [6] and publications [7,8].

The scattering parameter method was utilized in order to conduct a full analysis of the uncertainty of the measurement accuracy parameter matrix S of the elements of the measurement channel on the computed values of the parameters of the electrostatic discharge current generator.

The computations were performed as follows:

1) each of the scattering parameters $S_{11}{}^T$, $S_{12}{}^T$, $S_{21}{}^T$, $S_{22}{}^T$, $S_{11}{}^K$, $S_{12}{}^K$, $S_{21}{}^K$, $S_{22}{}^K$, $S_{11}{}^O$ was adjusted by the absolute delta value obtained from calculations $\Delta S_{11}{}^T$, $\Delta S_{12}{}^T$, $\Delta S_{21}{}^T$, $\Delta S_{22}{}^T$ according to equations (9) to (12), or measurements $\Delta S_{11}{}^K$, $\Delta S_{12}{}^K$, $\Delta S_{21}{}^K$, $\Delta S_{22}{}^K$, $\Delta S_{11}{}^O$, where only one parameter was modified each time.

2) the value of each of the parameters was increased and decreased by the absolute value of the error without a change in the phase, for each of the nine cases according to the following formula:

$$(5)\qquad S_{\text{var}}=S\pm\Delta S e^{j\arg S}$$

3) for each case, the input transfer impedance value was computed and the observed wave was analyzed.

4) the impedance and parameter values of the impulse current were compared with these parameters obtained without considering the uncertainty of the analyzer

5) absolute error values of related to these comparisons were computed

6) finally, standard deviation was computed by summing up specific relative errors as a square root of the sum of their squares according to the following formula:

$$(6)\qquad \delta x=\sqrt{\delta^2_{X_{S_{11}^T}}+\delta^2_{X_{S_{12}^T}}+\delta^2_{X_{S_{21}^T}}+\delta^2_{X_{S_{22}^T}}+\delta^2_{X_{S_{11}^K}}+\delta^2_{X_{S_{12}^K}}+\delta^2_{X_{S_{21}^K}}+\delta^2_{X_{S_{22}^K}}+\delta^2_{X_{S_{11}^O}}}$$

Parameter x present in this formula relates to each of the parameters of the current (T_r, U_{max}, U_{60}, U_{30}).

While determining the influence of the target parameters (ΔS), direct measurements of the network analyzer were not available. Instead, only absolute error values from measurements using this analyzer configured as adapter-target and adapter-adapter were used. Therefore, the absolute error of the S parameter of the target was computed using the following formula (7). It can be shown when accepting assumptions: adapters A and B are identical and have the symmetric matrices S: $S_{12}{}^A=S_{12}{}^B=S_{21}{}^A=S_{21}{}^B$

and that the adapters do not bounce: $S_{11}{}^A=S_{22}{}^A=S_{11}{}^B=S_{22}{}^B$

$$(7)\qquad S^A=S^B=\begin{bmatrix}0 & \sqrt{S_{12}^{AB}}\\ \sqrt{S_{21}^{AB}} & 0\end{bmatrix}$$

$$(8)\qquad S_{12}^A=\sqrt{S_{12}^{AB}}\rightarrow\Delta S_{12}^A=\frac{1}{2\sqrt{S_{12}^{AB}}}\Delta S_{12}^{AB}$$

Values of $\Delta S_{21}{}^{AT}$ were obtained directly from the measurement uncertainty of the scattering parameters. For the adapter-target configuration (AT) it was assumed that $\Delta S_{12}{}^{AT}=\Delta S_{21}{}^{AT}$.

Total differential method was used to compute the following values

$$(9)\qquad \Delta S_{11}^T=\sqrt{\left(\left|\frac{1}{S_{12}^A\cdot S_{21}^A}\right|\right)^2\cdot\left(\Delta S_{11}^{AT}\right)^2+\left(\left|-\frac{S_{11}^{AT}}{\left(S_{12}^A\right)^2\cdot S_{21}^A}\right|\right)^2\cdot\left(\Delta S_{12}^A\right)^2+\left(\left|-\frac{S_{11}^{AT}}{S_{12}^A\left(S_{21}^A\right)^2}\right|\right)^2\cdot\left(\Delta S_{21}^A\right)^2}$$

$$(10)\qquad \Delta S_{12}^T=\sqrt{\left(\left|\frac{1}{S_{12}^A}\right|\right)^2\cdot\left(\Delta S_{12}^{AT}\right)^2+\left(\left|-\frac{S_{12}^{AT}}{\left(S_{12}^A\right)^2}\right|\right)^2\cdot\left(\Delta S_{12}^A\right)^2}$$

$$(11)\qquad \Delta S_{21}^T=\sqrt{\left(\left|\frac{1}{S_{21}^A}\right|\right)^2\cdot\left(\Delta S_{12}^{AT}\right)^2+\left(\left|-\frac{S_{21}^{AT}}{\left(S_{21}^A\right)^2}\right|\right)^2\cdot\left(\Delta S_{21}^A\right)^2}$$

$$(12)\qquad \Delta S_{22}^T=\sqrt{\left(\Delta S_{22}^{AT}\right)^2}$$

The analysis and simulation confirmed that the positive and negative variances match.

Measurement and Computation Results

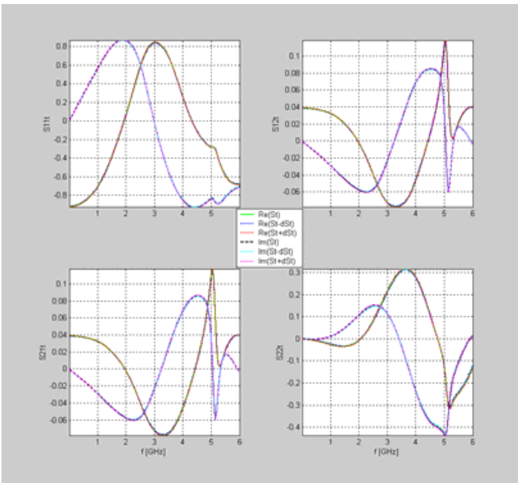

Fig. 3. Graphs of the $S(f)$ target parameters with bands showing the uncertainty $\Delta S(f)$

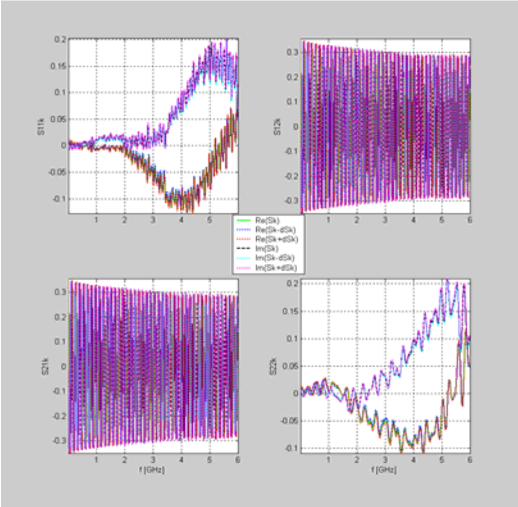

Fig. 4. Graphs of the *S(f)* cable parameters with bands showing the uncertainty *ΔS(f)*

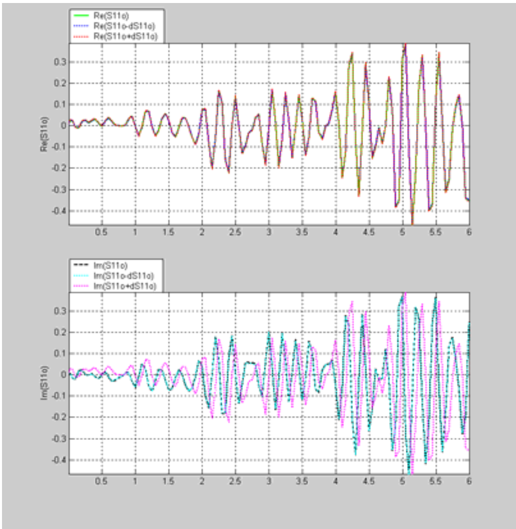

Fig. 5. Graph of parameter $S_o(f)$ of the oscilloscope with bands showing uncertainty $\Delta S_o(f)$

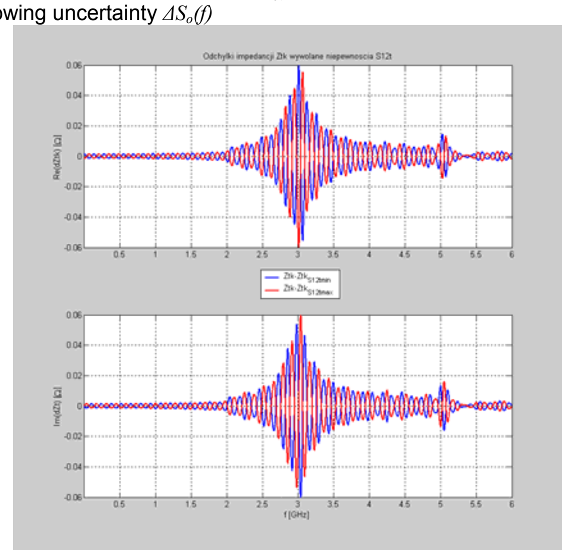

Fig. 6. Deviation of the transfer impedance $\Delta Z_{tk}(f)$ related to the uncertainty of the measurement S_{12t} showing highest sensitivity to the change of Z_t

Conclusions and Summary

Having Analysis of the results shown in tables in [6] and sample graphs presented in the thesis (more graphs have been presented in [6]) leads us to the following conclusions:

- Zero values of the error of the ascending wave parameter δ_{Tr} should be interpreted as errors below sensitivity threshold($< 0.0001\%$).

- Parameter S_{21}^T has the highest influence on the output voltage of the target (an error of approximately 0.44%). Changes in the value of S_{11}^T result in an error of approximately $0.16\ \%$. The simulations did not show any dependency on S_{12}^T and S_{22}^T

- Oscilloscope input voltage shows the highest sensitivity to the changes in S_{12}^T (of approximately $0.44\ \%$), as well as changes in S_{12}^K (error of $0.29\ \%$). No impact of parameters S_{21}^K and S_{22}^K was detected, and minimal impact of S_{11}^T and S_{11}^O was detected (error of approximately $0.15\ \%$).

Shown below are absolute total error values that represent the influence of all elements of the measurement channel on the parameters of the impulse current of the electrostatic discharge in two cases:

The first case relates to the optimal width of the time-interval in the tested frequency range ($250\ ns$, $4\ GHz$).

The second case relates to the selection of the analysis window ($500ns$) and the maximum frequency range ($6GHz$).

Absolute error values of the electrostatic discharge current, including the high-frequency characteristics of the elements of the measurement channel (δ_{cTr}, δ_{CUmax}, δ_{cu30}, δ_{cu60}) are represented by equations (13) to (16), and the total error of the scattering sensitivity method (δ_x) is given by (6). Cumulative relative errors representing the component values are expressed below

(13) $$\delta_{cwTr} = \sqrt{\delta_{cTr}{}^2 + \delta_{wTr}{}^2}$$

(14) $$\delta_{cwU_{MAX}} = \sqrt{\delta_{cU_{MAX}}{}^2 + \delta_{wU_{MAX}}{}^2}$$

(15) $$\delta_{cwU_{30}} = \sqrt{\delta_{cU_{30}}{}^2 + \delta_{wU_{30}}{}^2}$$

(16) $$\delta_{cwU_{60}} = \sqrt{\delta_{cU_{60}}{}^2 + \delta_{wU_{60}}{}^2}$$

For the first case ($T_0 = 250\ ns$, $f = 4\ GHz$) the errors are computed as

(17) $$\delta_{cwTr} = \sqrt{(3.6)^2 + (0)^2} = 3.6\%$$

(18) $$\delta_{cwU_{MAX}} = \sqrt{(1.38)^2 + (0.55)^2} = 1.48\%$$

(19) $$\delta_{cwU_{30}} = \sqrt{(0.85)^2 + (0.57)^2} = 1.02\%$$

(20) $$\delta_{cwU_{60}} = \sqrt{(1.11)^2 + (0.55)^2} = 1.24\%$$

For the second case ($T_0 = 500ns$, $f = 6\ GHz$) the following errors were obtained

(21) $$\delta_{cwTr} = \sqrt{(0)^2 + (0)^2} = 0\%$$

(22) $$\delta_{cwU_{MAX}} = \sqrt{(1.58)^2 + (0.56)^2} = 1.67\%$$

(23) $$\delta_{cwU_{30}} = \sqrt{(0.95)^2 + (0.57)^2} = 1.1\%$$

(24) $$\delta_{cwU_{60}} = \sqrt{(1.02)^2 + (0.55)^2} = 1.15\%$$

Analysis of the results presented in the tables included in this paper [6] and example graphs presented in this paper (the other charts in this paper [6]) allows to make the following observations:

- error zero values for parameter rise time δ_{Tr} must be interpreted as meaning that the errors actually occurring are below the accuracy of calculations ($<0.0001\%$).
- The strongest influence on the output voltage of the shield have the parameter change S_{21}^T (error of about 0.44%). While the parameter change S_{11}^T will result in an error of about 0.16%. Conducted simulations have shown no link between this voltage from changing parameters S_{12}^T and S_{22}^T.
- Voltage input of the oscilloscope shows the greatest sensitivity to changes in parameters S_{12}^T (error of about 0.44%), as well as the parameter change (error of about 0.29%). There was no effect on the value of this voltage change parameters and, while the impact parameters, and is minor (error of about 0.15%).
Below are dependencies (in the form of relative total errors), allowing to determine the impact of all elements of the measurement path on the parameters of the current pulse electrostatic discharge, for two cases.
The first case concerns the selection of the optimal values of the width of the time window and issue frequency range (*250ns*, *4 GHz*).
The second case concerns the selection of the analysis window (*500ns*) and maximum frequency range (*6 GHz*).
Relative total errors individual parameters of current waveform electrostatic discharge, taking into account the properties of the high frequency elements of the measuring path (δ_{cTr}, δ_{CUmax}, δ_{cu30}, δ_{cu60}), define relationships from (13) to (16), while the total error according of the sensitivity method (δ_x) is given by the pattern(6). Total values of the relative errors taking into account mentioned above components define relationships 13,14,15,16. For the first of the following cases ($T_0 = 250ns$, $f = 4\ GHz$), these errors are between 17 to 20. For the second case ($T_0 = 500ns$, $f = 6\ GHz$), an error value formulas from (21) to (25).

Analysis of the cumulative error values shows minimal influence (approximately 3rd significant digit) of the time-window and the measurement range of S parameters computed using the scattering sensitivity method.

Analysis of the errors shows that the time window of *250ns* and a *4GHz* measurement range are optimal for these measurements.

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